Technical and economical analysis of exploitation of gas fired small scale combined heat and power systems in Poland

Paper presents an estimation of influence of selected technical and financial parameters on the cost-effectiveness of the small scale cogeneration systems in Poland. The influence of electrical efficiency of the combined heat and power (CHP) module and power-to-heat ratio on the exploitation costs and incomes of the whole cogeneration system has been analysed. Analysis has been carried out on the example of small scale CHP with the reciprocating internal combustion (IC) gas engine or gas turbine fired by natural gas or coal bed methane.

1 Introduction

During two last decades one can observe in Poland an increase of number and total power of distributed power generation units fired by gas fuels (especially cogeneration units). More and more important share of them are small scale combined heat and power (CHP) systems [1,2]. Profits given by cogeneration technology are mainly of thermodynamic nature and leads to the possibility of decrease of primary energy consumption (and emissions to the environment) when comparing to separate power and heat generation. Majority of being under exploitation CHP units are of small scale and can be classified as distributed power generation systems. The most significant feature of distributed power generation units is in situ power consumption. The surplus of electricity can be sold to the grid.

More and more CHP units are fired by gaseous fuels due to the following important premises:

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• relatively high efficiency of power generation and low emissions,
• permanent technical improvement of new constructions of CHP modules (reciprocating gas engines, gas turbines and microturbines),
• low demand for the site,
• optimal sizing towards consumer demands,
• possibility of utilization of special fuels without fuel transportation (biogases, coal bed methane etc.).

Small scale cogeneration systems are installed usually in locations where demand for power and heat appears during significant part of the year. Usually, time distribution of power and heat demand changes during the day and depends on several factors, i.e., season, industrial technology etc. Variation and volume of demand for electricity and heat along twenty-four hours as well as seasonal profile of demand has an essential influence on size and configuration of cogeneration unit.

It should be stressed, that small scale distributed power generation units are in fact not competitors against large scale power plants. Moreover, are desirable supplement of electricity grid increasing the flexibility of grid operation. In industrial applications, the small scale CHP unit can cover electricity and heat demands for specific technological process. In that case CHP unit operates as a peak source of electricity.

All these mentioned reasons should stimulate development of small scale cogeneration systems. We should remember however, that the final decision for investment and specific CHP unit configuration should be result of technical and financial analysis.

2 Conditions of cost-effectiveness of cogeneration projects

Even the most beneficial technical indices of energy conversion and emissions are not crucial points to realize investment project of CHP unit. The most important premise is here positive economical effect. The measure of economical effectiveness (for example net present value (NPV), internal rate of return (IRR) etc.) depends on a great deal of factors. The most important of them are:

• time variation of power and heat demand,
• prices of fuel, electricity, heat and certificates of origin,
• structure of CHP system and technical parameters: power level, efficiency (heat rate), power-to-heat ratio, exploitation characteristics,

• operation mode of CHP.

The most promising effects are achieved for optimally selected technical and economical circumstances.

According to the being if force standards the measure of economical effectiveness are discounted indices of the cost-effectiveness: net present value (NPV), internal rate of return (IRR) and payback period (DPB). The project is profitable if positive financial effect is achieved, i.e., NPV > 0. Moreover the payback period DPB and internal rate of return IRR should satisfy expectation of investor. Eventually the economical effectiveness of CHP project depends on great deal of factors, which can be classified into two groups:

a) Technical and exploitation factors (microeconomical):

• efficiency of power and heat generation (relatively high for gas fired units),

• annual level of utilization of nominal power and heat load,

• unitary investment cost of gas fired CHP units (lower than for other power generation technologies),

• time of start-up of CHP unit (very short for gas fired units: gas turbines and IC engines);

• possibility of optimal sizing of nominal power of the unit,

• environmental impact (low for gas fired units),

• site demand (very low for gas fired units).

b) Macroeconomic factors:

• the cost of investment capital (value of the rate of discount),

• cost of fuel (i.e., cost of natural gas),

• electricity prices (level and daily/annual variations),

• heat prices,

• prices of certificates of origin for electricity generation in high-efficient cogeneration (‘yellow’, ‘violet’ and ‘red’ certificates),

• prices of certificates of origin for electricity generation base on the renewable primary energy sources (‘green’ certificates),
• costs of emissions to the environment (including cost of commissions for CO₂ emission).

Several relationships among technical/operational factors can be derived. These relationships allows us to optimally select the structure of the power generation system on the level of feasibility study analysis. Conclusions from that analysis can be very useful for technical optimization of the system and its exploitation conditions.

As a measure of economical effectiveness of the investment project one can assume net present value:

\[
NPV = \sum_{t=0}^{N} \frac{CF_t}{(1 + r)^t},
\]

where \( CF_t \) is the annual cash flow, \( t \) is the number of the year of exploitation (year of number zero represents total investment cost), \( r \) is the rate of discount for the project, and \( N \) is the period of exploitation (in years).

The project is cost-effective only when vale on \( NPV \) is greater than zero for \( N \) years of exploitation (\( NPV > 0 \)). If we assume that value of cash flow \( CF_t \) in successive years of exploitation are constant or similar, condition of cost-effectiveness of the project can be written as

\[
CF_t > 0.
\]

Cash flow consists of several items:

\[
CF_t \cong S - K - P = S - K - p(S - K - A - F),
\]

where \( S \) – total annual income, \( K \) – total annual exploitation cost, \( A \) – annual rate of depreciation, \( P \) – income tax, \( p \) – the rate of income tax (e.g., \( p = 19\% \)), \( F \) – financial costs (e.g., rate of interest). Taking into account that income tax \( P \) is always lower then difference between incomes \( S \) and costs \( K \) we can assume that condition \( CF_t \) can be fulfilled only when total income \( S \) is greater than total cost \( K \):

\[
\Delta S - K = S - K > 0 \quad \text{or} \quad \zeta_{S-K} = \frac{S}{K} > 1 \Rightarrow \max.
\]
• sale of electricity (or avoided purchase), $S_{el}$,
• sale of heat, $S_Q$,
• sale of certificates of origin for electricity generation in high-efficient cogeneration (‘yellow’, ‘violet’ and ‘red’ certificates) and prices of certificates of origin for electricity generation based on renewable primary energy sources (‘green’ certificates), $S_{co}$.

b) Costs $K$:

• cost of fuel, $K_f$,
• purchase of certificates of origin for electricity generation in high-efficient cogeneration (‘yellow’, ‘violet’ and ‘red’ certificates) and prices of certificates of origin for electricity generation based on renewable primary energy sources (‘green’ certificates),
• rate of depreciation, $K_d$,
• excise tax for sale of electricity, $K_{el}$ (paid by supplier of electricity to enduser).

For the most common in practice gas fired CHP systems, i.e., fired by natural gas, the crucial influence on the cost-effectiveness of the project have only few (exactly four) items: $S_{el}$, $S_Q$, $S_{co}$ and $K_f$.

Sale of electricity generate an income

$$S_{el} = E_{els}c_{el}, \quad (5)$$

where $E_{els}$ is an amount of electricity being sold, and $c_{el}$ is an average unitary price of electricity.

Sale of heat generate an income

$$S_Q = Qc_Q, \quad (6)$$

where $Q$ is an amount of heat being sold, and $c_Q$ is an average unitary price of heat.

Relationship between amount of electricity $E_{els}$ and amount of heat $Q$ defines exploitation (real) power-to-heat rate

$$\sigma = \frac{E_{els}}{Q}, \quad (7)$$

hence

$$S_Q = \frac{E_{els}}{\sigma}c_Q. \quad (8)$$
Sale of certificates of origin generates an income

\[ S_{sc} = E_{el,CHP}c_{sc}, \quad (9) \]

where \( E_{el,CHP} \) [MWh] is an amount of electricity which can be classified as being generated in high-efficient cogeneration.

In Poland an amount of electricity which can be classified as being generated in high-efficient cogeneration results from general formula [3,4]:

\[ E_{el,CHP} = \beta E_{el}, \quad (10) \]

where \( E_{el} \) denotes total (gross) amount of electricity produced in CHP unit. The value of parameter \( \beta \) can vary from 0 to 1. Specific value of \( \beta \) depends mainly on total efficiency of CHP unit \( \eta_{CHP} \) and coefficient of primary energy savings (PES). It is required [4] to comply the conditions PES > 10% or PES > 0 to obtain the certificates of origin from generation of electricity in high-efficient cogeneration. If coefficient PES satisfy mentioned conditions, value of parameter \( \beta \) depends mainly on value of total efficiency of CHP unit

\[ \eta_{CHP} = \frac{E_{el} + Q}{E_{chf}} = \frac{E_{el} + E_{el}/\sigma}{E_{chf}}, \quad (11) \]

where \( E_{chf} \) is the consumption of chemical energy of fuel in CHP unit, and \( Q \) is the amount of heat supplied to endusers.

Main element of exploitation costs of CHP unit fired by natural gas is the cost of fuel

\[ K_{chf} = E_{chf}c_{chf}, \quad (12) \]

where \( c_{chf} \) is the unitary cost of chemical energy of fuel (e.g., PLN/GJ). An amount of chemical energy of fuel \( E_{chf} \) and amount (gross) of electricity \( E_{el} \) define very important technical parameter of CHP module, i.e., electric efficiency,

\[ \eta_{el} = \frac{E_{el}}{E_{chf}}, \quad (13) \]

An amount of electricity which is sold from CHP \( E_{els} \) is always smaller than amount of electricity produced by CHP \( E_{el} \) because the part of electricity should cover own needs of CHP unit

\[ E_{els} = (1 - \varepsilon_w)E_{el}, \quad (14) \]

where parameter \( \varepsilon_w \) usually cover the value from 0.03 to 0.07.

When analyzing relationships defining specific elements of cash flow it is possible to separate those parameters, which have the most important influence on the cost-effectiveness of gas fired cogeneration unit:
a) Technical parameter:
  - efficiency of power generation, $\eta_{el}$

b) Operational parameter:
  - real (operational) power-to-heat ratio, $\sigma$

c) Price parameters:
  - the price of chemical energy of fuel, $c_{chf}$
  - price of electricity (sale or avoided purchase), $c_{el}$
  - price of certificate of origin $c_{co}$.

It would be very difficult to derive even estimate, but general, relationships which could show the influence of above mentioned parameters on cost-effectiveness of the cogeneration project (the large number of statistical data should be considered). It is however possible when analyzing smaller groups of similar project (in the sense of technical and macroeconomics circumstances). Results of such an analysis for small scale cogeneration project is shown in the next chapter. CHP unit is fired by natural gas or coal bed methane.

3 Analysis of sample small-scale cogeneration project

Analysis of the influence of most important technical, operational and financial parameters on the cost-effectiveness of cogeneration project has been carried out on the sample of the small scale CHP unit (about 6 MW of thermal load) with IC engine (Fig. 1) or gas turbine (Fig. 2). Main technical differences between these two devices are: efficiency of power generation and nominal heat-to-electricity ratio (Tab. 1). CHP system produces electricity and hot water for heating purposes. Electricity is being sold to enduser (via separate electric cable) when hot water is being sold to the local heating network. Hot water covers heat demand according to given heat load duration profile (Fig. 3). CHP system is supplied by gas fired boiler to cover peak heat demand. Maximum heat demand is on the level of 9.5 MW$_{th}$. It is assumed that CHP covers heat demand at the base of load, i.e., about 6 MW$_{th}$. Higher heat loads are covered by gas fired water boiler.

As it was mentioned CHP unit can be fired by two different fuels of radically different prices:
Figure 1. Scheme of CHP unit with IC reciprocating engine.

Figure 2. Scheme of CHP unit with gas turbine.
a) natural gas (unitary price $c_{ch,f} = 40$ PLN/GJ),

b) coal bed methane (unitary price $c_{ch,f} = 5$ PLN/GJ).

From the cost-effectiveness point of view difference in the unitary price has an crucial meaning: price of coal bed methane is 8 times lower, what means lower share of fuel cost within total exploitation cost.

To provide reliable comparison of cost-effectiveness of CHP projects it has been assumed, that selection of technical parameters of IC engine and gas turbine results from matching in the heat demand side. It means (Fig. 3), that nominal heat load of IC engine and gas turbine lies in the range $6-7$ MW$_{Th}$. Specific technical parameters of selected (from producers offers) machines are presented in Tab. 1. We can see, that for comparable nominal heat loads IC engine represents much more higher electrical efficiency as well as nominal power-to-heat ratio.

<table>
<thead>
<tr>
<th></th>
<th>IC gas engine (2 pieces)</th>
<th>Gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal heat load*, MW$_{Th}$</td>
<td>6.09</td>
<td>6.76</td>
</tr>
<tr>
<td>Nominal electric power, MW$_{el}$</td>
<td>6.71</td>
<td>3.52</td>
</tr>
<tr>
<td>Electrical efficiency, %</td>
<td>44.9</td>
<td>27.9</td>
</tr>
<tr>
<td>Nominal power to heat ratio $\sigma_{nom}$</td>
<td>1.1</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* Flue gases are cooled to 120 °C

Annual operational technical parameters of CHP systems have been calculated on the base of technical data of machines and heat load duration profile (see Tab. 2). Annual operation time is assumed 8500 h.

From analysis of data presented in Tab. 2 we can derive several important conclusions according to technical operational parameters of the CHP system:

- CHP with gas turbine provides much lower nominal and operational power-to-heat ratio (it results mainly from relatively low electric efficiency of gas turbine).
- Level of utilization of nominal heat load from the modules with IC engine and gas turbine is similar.
- Total efficiency of CHP module with IC engine is much more higher (for similar heat load IC engine produces much more electricity).
- Coefficient of Primary Energy Savings PES for CHP system with gas turbine is equal to 8.3% (is lower than 10% limit). It means that in spite of
Table 2. Specific annual operational parameters of CHP systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Unit</th>
<th>IC engine (2 pieces)</th>
<th>Gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power in the fuel to CHP module</td>
<td>MW</td>
<td>14.94</td>
<td>12.92</td>
</tr>
<tr>
<td>Nominal power-to-heat ratio, $\sigma_{\text{nom}}$</td>
<td></td>
<td>1.10</td>
<td>0.52</td>
</tr>
<tr>
<td>Fuel consumption (chemical energy) if CHP module</td>
<td>GJ</td>
<td>457 160</td>
<td>386 065</td>
</tr>
<tr>
<td>Fuel consumption (chemical energy) in CHP module</td>
<td>GJ</td>
<td>4 488</td>
<td>3 176</td>
</tr>
<tr>
<td>Electricity produced (gross)</td>
<td>MWh</td>
<td>57 018</td>
<td>29 920</td>
</tr>
<tr>
<td>Electricity produced (net)</td>
<td>MWh</td>
<td>55 307</td>
<td>29 022</td>
</tr>
<tr>
<td>Electricity produced in high-efficient cogeneration</td>
<td>MWh</td>
<td>45 861</td>
<td>0 (18412)</td>
</tr>
<tr>
<td>Total efficiency of CHP [3]</td>
<td>%</td>
<td>69.11</td>
<td>57.1</td>
</tr>
<tr>
<td>Coefficient of primary energy savings PES [3]</td>
<td>%</td>
<td>19.80</td>
<td>8.30</td>
</tr>
<tr>
<td>Heat sold from CHP module</td>
<td>GJ</td>
<td>110 830</td>
<td>111 899</td>
</tr>
<tr>
<td>Heat sold from water boiler</td>
<td>GJ</td>
<td>4 023</td>
<td>2 954</td>
</tr>
<tr>
<td>Operational power-to-heat ratio, $\sigma$</td>
<td></td>
<td>1.85</td>
<td>0.96</td>
</tr>
<tr>
<td>Utilization of nominal heat load from CHP module ($\sigma/$\sigma_{\text{nom}}$)</td>
<td></td>
<td>0.595</td>
<td>0.543</td>
</tr>
</tbody>
</table>

relatively high total efficiency it is impossible to get certificates of origin for the electricity produced in high efficient cogeneration.

- An amount of fuel fired in water peak boilers is very small (on the level of 1%).

As the next step the prefeasibility study of cost-effectiveness of the CHP projects has been derived. Four case studies was analyzed: (IC engine, gas turbine, natural gas, coal bed methane) to calculate cost-effectiveness indices (NPV, NPVR, IRR,
DPB). Following assumptions and values were taken into analysis (prices without VAT tax):

- discount rate: 8.9%,
- exploitation time: 12 years,
- price of natural gas (average): 40 PLN/GJ,
- price of coal bed methane (average): 5 PLN/GJ,
- price of electricity (sale to enduser, average): 295 PLN/MWh,
- price of heat (average): 35 PLN/GJ,
- price of certificate of origin ‘yellow’: 128 PLN/MWh,
- price of certificate of origin ‘violet’: 55 PLN/MWh.

The results of calculations of cost-effectiveness indices are presented in Tab. 3. Shares of the most important cash flow items (incomes and costs) are shown in Tab. 4. To simplify the analysis it was assumed, that depreciation charges are constant for each year of exploitation time.

### Table 3. Cost-effectiveness indices for CHP projects.

<table>
<thead>
<tr>
<th></th>
<th>Natural gas</th>
<th>Coal bed methane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IC engine</td>
<td>Gas turbine</td>
</tr>
<tr>
<td>Total investment</td>
<td>million PLN</td>
<td></td>
</tr>
<tr>
<td>cost CNI</td>
<td>19.2</td>
<td>14.0</td>
</tr>
<tr>
<td>NPV</td>
<td>8.300</td>
<td>-53.8</td>
</tr>
<tr>
<td>NPVR = NPV/CNI</td>
<td>0.432</td>
<td>-3.9</td>
</tr>
<tr>
<td>DPB</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>IRR</td>
<td>16.3</td>
<td></td>
</tr>
</tbody>
</table>

Results in Tabs. 3 and 4 show, that for CHP which is fired by relatively expensive fuel (natural gas) cost-effectiveness is positive (but barely) only for the system with IC engine. CHP with gas turbine is not profitable. It results mainly due to the low electrical efficiency of the gas turbine together with high share of fuel cost (absolute and relative). Even for CHP system with IC engine the ratio of annual incomes to annual costs is only slightly greater than unity, so the cost-effectiveness indices are very sensitive to the even very small changes of prices and exploitation parameters. Cost-effectiveness of the project considerably improves for coal bed methane fired CHP systems. Cost of fuel is here much more lower. For the same incomes we have nearly twice smaller costs (the share of fuel cost...
Table 4. Share of main streams of annual incomes and costs.

<table>
<thead>
<tr>
<th></th>
<th>Natural gas</th>
<th>Coal bed methane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IC engine</td>
<td>Gas turbine</td>
</tr>
<tr>
<td>Incomes (annual, net)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sell of electricity to enduser, %</td>
<td>62.3</td>
<td>70.3</td>
</tr>
<tr>
<td>Sell of heat, %</td>
<td>15.3</td>
<td>29.7</td>
</tr>
<tr>
<td>Sell of certificates of origin ('yellow' for natural gas and 'violet' for coal bed methane), %</td>
<td>22.4</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Costs (annual, net)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of fuel for CHP module, %</td>
<td>76.8</td>
<td>81.6</td>
</tr>
<tr>
<td>Cost of fuel for water boiler, %</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Cost of purchase of 'green' certificates of origin, %</td>
<td>6.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Annual depreciation charge, %</td>
<td>6.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Excise tax for electricity, %</td>
<td>4.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Operation and maintenance costs (inspections, repairs, overhaul, oil, filters etc.), %</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Cost of wages, %</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Cost of certificates of origin ('green', 'yellow', 'red' and 'violet'), %</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Cost of emission (without cost of commissions for CO₂ emission), %</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Ratio incomes/costs</td>
<td>1.18</td>
<td>0.65</td>
</tr>
</tbody>
</table>

in total cost is here on the level only 30–35%). As the result even for the CHP system with gas turbine one achieves very profitable cost-effectiveness indices (as for projects in power generation area). From the structure of incomes results, that for all analyzed cases the most important share has the sell of electricity and the sell of certificates of origin for the electricity from high-efficient cogeneration (from 68 to 85% of total income).

4 Conclusions

Several conclusions can be derived from presented analysis according to the technical and economical circumstances of small scale cogeneration projects in Poland in distributed power generation area:

- Electrical efficiency $\eta_{el}$ of CHP module is the basic technical parameter which influences cost-effectiveness of the project.
• Real electricity-to-heat ratio $\sigma$ is the basic operational parameter which influences cost-effectiveness of the project.

• Price of chemical energy of fuel $c_{chf}$, price of electricity $c_{el}$ (sell or avoided purchase) and price of certificates of origin $c_{co}$ (sell and possible purchase) are the basic financial parameters which influence cost-effectiveness of the project.

• Cost of electricity is the most important parameter to obtain positive cost-effectiveness indices for the CHP systems fired by natural gas (expensive fuel). Hence it is purposeful to build CHP units which supply electricity directly to endusers or which cover own needs (avoided purchase of electricity).

• For CHP units fired by cheap fuel (e.g., coal bed methane) it is possible to obtain positive cost-effectiveness indices even for low electrical efficiency of the CHP module and low real electricity-to-heat ratios.

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References


Analiza uwarunkowań techniczno-ekonomicznych budowy gazowych układów kogeneracyjnych małej mocy w Polsce

Streszczenie

Przeprowadzono ocenę wpływu wybranych parametrów technicznych, eksploatacyjnych i cenowych na wskaźniki opłacalności budowy gazowych układów kogeneracyjnych małej mocy w Polsce. Określono wpływ sprawności elektrycznej modułu kogeneracyjnego (CHP – *combined heat and power*) i eksploatacyjnego wskaźnika skojarzenia na podstawowe składniki kosztów i przychodów z eksploatacji układu. Przeprowadzono analizę obliczeniową układu kogeneracyjnego z gazowym silnikiem tłokowym lub turbiną gazową zasilanych gazem ziemnym systemowym lub gazem z odmetanowania kopalń